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RESEARCH MEMORANDUM

PRELIMINARY TESTS TO DETERMINE THE MAXIMUM LIFT OF WINGS AT SUPERSONIC SPEEDS

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY TESTS TO DETERMINE THE MAXIMUM LIFT OF WINGS AT SUPERSONIC SPEEDS

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SUMMARY

An exploratory test program was carried out in the Langley 9-inch supersonic tunnel to determine the maximum lift of wings operating at supersonic speeds. A variety of wing plan forms of random thickness distribution were tested at Mach numbers of 1.55, 1.90, and 2.32 and Reynolds numbers varying between 0.3×10^6 and 0.7×10^6 at angles of attack ranging from zero up through the angle at which maximum lift occurred. In general, at these Mach numbers the value of maximum lift coefficient was approximately 1.05 ± 0.05; it appeared to be independent of plan form and decreased slightly with increasing Mach number. No discontinuities in lift occurred from zero angle of attack through maximum lift, which was attained at approximately 40° angle of attack. In the Mach number range tested, the lift curves remained linear as high as 20° to 30° angle of attack. Lift-drag ratios at maximum lift were of the order of 1.0.

INTRODUCTION

The designer of supersonic aircraft – particularly the guided-missile designer – is interested in the maximum loads that can be attained on wings operating at supersonic speeds. The need for such maximum-load information is obvious in determining the maximum accelerations that can be attained by supersonic aircraft and in the structural design of aircraft components. To provide maximum lift and drag information, tests of 10 wings to high angles of attack were made in the Langley 9-inch supersonic tunnel. Only available models were used; hence no comprehensive study of plan form and wing section was made. The tests were concerned mainly with plan form inasmuch as it was felt that this was the primary variable.

SYMBOLS

V	stream velocity
M	stream Mach number
ρ	stream density
μ	stream viscosity
q	dynamic pressure $\left(\frac{1}{2}\rho V^2\right)$
R	Reynolds number referred to c $\left(\frac{\rho V_c}{\mu}\right)$
b	maximum wing span
c	maximum wing chord in stream direction
S	wing area
A	aspect ratio $\left(\frac{b^2}{S}\right)$
t	maximum thickness of wing
t/c	thickness ratio of wing in stream direction
C_L	lift coefficient $\left(\frac{\text{Lift}}{qS}\right)$
C_D	drag coefficient $\left(\frac{\text{Drag}}{qS}\right)$
α	angle of attack, degrees
ϵ	triangular wing vertex half-angle, degrees
θ	wing-tip angle measured from stream direction, degrees
Λ	sweep angle of leading edge, degrees

APPARATUS AND TEST METHODS

Description of tunnel.- The Langley 9-inch supersonic tunnel is a closed-return wind tunnel in which the humidity and temperature of the air can be controlled with suitable drying and cooling equipment. The test Mach number is varied by the use of interchangeable nozzle blocks which form test sections approximately 9 inches square. Models are mounted in the tunnel on shielded stings and the forces are measured on a three-component balance system. The range of the externally controllable angle-of-attack mechanism is ±5°.

Description of models and supports.- The models tested are shown in figure 1 and pertinent dimensions are given in table I. The two trapezoidal wings ($\theta = 30^\circ$ and $\theta = 40^\circ$) were made by obliquely cutting off the tips of rectangular wings which had symmetrical circular-arc airfoil sections. The trapezoidal wings were tested with both bluff and beveled tips. The rectangular wings had symmetrical circular-arc airfoil sections. The 63° and 45° swept wings had modified symmetrical circular-arc airfoil sections perpendicular to the leading edges. The modifications entailed rounding the leading edges and beveling the tips. The triangular wings were flat plates with leading edges beveled slightly and rounded off and trailing edges beveled to a sharp edge. A more complete description of these swept and triangular wings is given in reference 1. The 36° swept wing had the same airfoil section and tip bevel as the other swept wings, but its tips were cut off parallel to the stream direction.

Various stings (fig. 2) were used to support the models in the tests. For most of the tests the windshield shown in figure 3 was used; however, some tests were made using the long windshield shown in figure 4. The combinations of the various wings and their supports are summarized in table II.

Test methods.- The limited range of the tunnel angle-of-attack mechanism (±5°) made it necessary to devise some means for the tests which would allow larger angles to be reached. The angle-of-attack range was covered by bending the sting (fig. 2) successively in 10° increments, filling in smaller incremental angles with the angle-of-attack mechanism.

The first set of data taken at $M = 2.32$ using sting "a" showed displacements of successive groups of test points (approximately 10° increments between "sting bends") in the lift results as shown in figure 5. These displacements in the lift curves suggested that the forces on the sting might be larger than had originally been expected. The maximum displacement of the test-point groups in the region of maximum lift occurred for the smallest area wing (fig. 5(b)) and was of the order of 6 percent. Only small displacements are to be noted in the drag curves.

Because of the displacements in the test-point groups indicated in the results at $M = 2.32$ using sting "a," sting "b" (fig. 2) was used in the next series of tests at $M = 1.55$ (fig. 6) in an attempt to reduce the forces on the model support. The maximum displacement of the test-point groups in the region of maximum lift occurred as in the

M = 2.32 tests for the smaller area wings, but was about 5 percent (figs. 6(b) and 6(f)). The displacements for the majority of the configurations, however, were considerably less. The displacements in the drag test-point groups were again small as compared with the lift results.

Even though the shorter sting reduced the magnitude of the discontinuities in the lift curves, the absolute values of the forces on the model supports were still not known. In an attempt to evaluate these forces, eight pairs of static orifices were installed on sting "b" and run at M = 1.55 for the configurations indicated in table II. The corrected lift data are shown in figures 6(a), 6(b), 6(f), and 6(g). The long windshield was used in addition in an attempt to minimize the forces on the model support as much as possible and provide an additional comparative value of lift close to maximum lift.

The previous tests showed good agreement between the values of maximum lift obtained by correcting for the sting pressures and by the use of the long windshield; therefore, in the next series of tests, only the long windshield was used to obtain check data. For the tests at M = 1.90, sting "b" was again employed and, because of the reduction in the magnitude of the lift-curve displacements in going from sting "a" to sting "b," a still shorter model support, sting "c," was also employed. The tests at M = 1.90 were run at angles of attack in the region of maximum lift only.

PRECISION OF DATA

It should be realized that the primary purpose of the tests was to obtain values of maximum lift. Data obtained at the lower angles were not expected to be as accurate as those obtained at the higher angles because the test technique employed was one of convenience. Furthermore, no reasonable values of pitching moment were obtained because the lack of sufficient instrumentation made it impossible to evaluate the magnitude and location of the resultant force on the sting.

The total forces on the models and supports were measured on self-balancing beam scales. The maximum probable errors in the scale measurements are of the order of a small fraction of 1 percent of the forces at maximum lift and thus appear negligible in comparison with the other errors involved in evaluating the forces on the model supports. The differences in values obtained by the various model-support schemes thus remain the only means of judging the accuracy of the maximum-lift results.

Maximum lift.- The lack of any previous information on maximum lift at supersonic Mach numbers made the check-point runs in these tests necessary. Most of the information regarding accuracy was obtained at M = 1.55; however, some additional checks were made at M = 1.90. The data corrected for the pressure forces at maximum lift (shown in figs. 6(a), 6(b), 6(f), and 6(g)) checked the uncorrected lift values within 5 percent except for the trapezoidal wing for which there was an 8-percent discrepancy. The obtainment of sufficient pressure readings along the sting for precise evaluation of the pressure forces would have been a prohibitively tedious process. Thus, because of the unknown precision of evaluating the lift component of the spindle pressure forces, an evaluation of the precision of the uncorrected results is not directly possible. The fact that the pressure corrections have taken most of the 10°-increment displacements out of all the lift curves (with the exception of fig. 6(b)) does, however, lend credence to the validity of the pressure corrections. It appears from the data that the difference between the uncorrected and corrected values of maximum lift is indicated as a reduction in the corrected value of about 5 percent. The data obtained with the long windshield covering the stings fell between the uncorrected data and the data corrected by use of the sting pressures. The long windshield data differed by 2 to 4 percent from the uncorrected data with the exception of the trapezoidal wing which still disagreed by 8 percent. Further check runs at $M = 1.90$ (fig. 7) with the long windshield checked the uncorrected lift data obtained with sting "b" within approximately 7 percent or less, and sting "c," within 3 to 4 percent. Since, in general, the various methods show a scatter in the order of 0.05 for maximum lift coefficient, it is felt that the results are probably significant to 0.05.

Drag at maximum lift.– An insufficient number of pressure tubes was installed on the stings to allow a reasonable value of sting drag to be obtained from integration of these pressures. The only method thus available is found in the use of the long windshield. Figures 6(a), 6(b), 6(f), and 6(g) show that the uncorrected drag is about 4 to 6 percent higher than the data obtained with the long windshield. Tests run at $M = 1.90$ show approximately the same error.

Lift at low angles.– The magnitude of the sting forces at the lower angles of attack could not be very easily evaluated; thus, a comparison of data in reference 1 for identical wings with short stings lends itself to a convenient check. The only wings in reference 1 for which a reasonable angle-of-attack range was run were the triangular wings $\epsilon = 26^{\circ}$ and $\epsilon = 45^{\circ}$ at $M = 1.43$ and $M = 1.71$. Comparisons with low-angle data ($\alpha = 0^{\circ}$ to 4°) presented in this report show that lift and lift-curve slopes herein presented at $M = 1.55$ with sting "b" are about 9 to 11 percent lower compared with reference 1, for which a direct interpolation for Mach number was made. It is realized that two configurations do not afford conclusive evidence as to the accuracy of the data; it is felt, however, that the other data will compare equally as well in precision. Furthermore, the check points were made with the smaller area wings where the sting forces represent a greater percentage of the total force; thus, the data for the larger area wings are probably more accurate.

Drag at low angles.– Drag checks similar to the lift checks were made with data presented in reference 1. The value of drag coefficient ($M = 1.55$) with sting "b" checked those of reference 1. The drag-coefficient values obtained from reference 1 were corrected as indicated therein.

Values of minimum drag coefficient presented in this report are approximately 0.01 higher than those of reference 1. This higher drag is probably due to differences between the sting configurations. The stings in the present tests were much longer than those in reference 1; and, at zero lift, the sting on the wings in reference 1 was at 0° angle of attack, while for the present data at zero lift, the rear portions of the stings were at −5° angle of attack. Values of minimum drag coefficient taken from the curves in this report will probably be too high and of doubtful value.

Stream surveys.– Stream surveys have indicated slight variations in stream Mach number and static pressure in the test section. The maximum variations measured for the test sections of the nozzles used in these tests are as follows:

Mach number	Maximum variation in Mach number (percent)	Maximum variation in stream pressure (percent)
1.55	±0.6	±1.3
1.90	±.5	±1.5
2.32	±.4	±1.5

It is felt that these variations do not affect the data to a sufficient extent to warrant discussion relative to the present tests.

RESULTS AND DISCUSSIONS

Lift and drag results for the various wings tested are presented in figures 6, 7, and 5 for Mach numbers of 1.55, 1.90, and 2.32, respectively. The Reynolds number per inch of chord for these test models varied between 0.37×10^6 at $M = 1.55$ and 0.27×10^6 at $M = 2.32$. The maximum

Reynolds number attained in these tests was 0.74×10^6 for the 63° sweptback wing at a Mach number of 1.55.

Lift Results

Maximum-lift region.- The value of the maximum lift coefficient for all configurations tested was practically constant for each Mach number regardless of varying plan forms. The maximum lift coefficient did vary slightly with Mach number, tending to decrease as the Mach number became greater. At a Mach number of 1.55, an average value of maximum lift coefficient for all configurations of approximately 1.10 was obtained, decreasing to 1.05 at $M = 1.90$ and further decreasing to 1.00 at $M = 2.32$. Table III summarizes the values of maximum lift coefficient of the various configurations at each Mach number. The angle of attack at which maximum lift coefficient occurred was approximately 40° for all Mach numbers and configurations.

Low-angle region.- The experimental lift curves, when faired through the intermediate values of each test-point group, are linear up to angles of attack as high as 20° for the 63° sweptback wing at $M = 1.55$, increasing to a value of 30° for the triangular $(\epsilon = 26^\circ)$ and 63° sweptback wings at $M = 2.32$. In general, the trend of the lift curves for all the wings was to remain linear to higher angles of attack as the Mach number increased. Owing to the fact that the value of the lifts of the stings – especially as affected by the different flow conditions behind the various wings – is not known, the only means for obtaining an indication of the precision of the results is by comparison with theory and other experiments. Comparisons of theoretical and experimental lift-curve slopes show the theoretical slopes to have deviations from a maximum of 50 percent greater (for the trapezoidal wing, $\theta = 40^\circ$, and tips beveled) to 6 percent less (for trapezoidal wing, $\theta = 30^\circ$, and tips not beveled) than the experimental slopes.

The experimental lift-curve slopes herein presented for the triangular wings $(\epsilon = 26^\circ$ and $\epsilon = 45^\circ)$ show deviations of 10 to 20 percent, respectively, less than theory, as compared with corresponding deviations of approximately 2 percent greater and 10 percent less for identical triangular wings of reference 1.

No general consistency is observed between the experimental and theoretical lift curves among the various plan forms or for given plan forms at the different Mach numbers.

Drag Results

Maximum-lift region.- The drag tare forces appear to be much more influenced by sting length than ~~the lift~~ forces; and an insufficient number of check points were obtained to give any reasonable value of drag coefficient for which a comparison could be made.

The value of the drag coefficient obtained at maximum lift is approximately 1.0; however, no significant indication of the variation of drag of any configuration with Mach number can be deduced because of the different sting lengths used at the various test Mach numbers.

Lift-drag ratios of the order of 1.0 were obtained at maximum lift. No significant differences in the value of this ratio are noted with change in plan form and Mach number.

Schlieren Photographs

Schlieren photographs of plan and side elevation views of two of the configurations at $M = 1.55$ are shown in figure 8 with both vertical and horizontal knife edges. The pictures mainly show by the strong shock ahead of the wing that, as would be expected, the wings constitute a very large disturbance to the flow. The side elevations are probably more interesting. It is difficult, however, to trace some of the disturbances to their origin. For instance, it is probable that the changes in density in the strong vortices from the region of the tips mask completely any view of the flow close to the wing surfaces; nevertheless, some disturbances can be traced to discontinuities such as the wing trailing edge. It appears that not a great deal can be learned from these schlieren photographs because the flow about the wing is three dimensional.

CONCLUSIONS

Supersonic-tunnel tests to determine the maximum lift of 10 wings of various plan forms and random thickness distribution at Mach numbers of 1.55, 1.90, and 2.32, and Reynolds numbers varying between 0.3×10^6 and 0.7×10^6 have indicated the following conclusions:

1. The average value of maximum lift coefficient was approximately 1.05 ± 0.05 and appeared to have no significant variation with plan form; however, the value decreased slightly with increasing Mach number.

2. The lift curve remained linear for angles of attack as high as 20° to 30°, and no discontinuities in lift occurred from zero up to and slightly above maximum lift.

3. Maximum lift was not obtained until an angle of attack of approximately 40° was reached.

4. Lift-drag ratios of approximately 1.0 were obtained at maximum lift.

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REFERENCE

1. Ellis, Macon C., Jr., and Hasel, Lowell E.: Preliminary Tests at Supersonic Speeds of Triangular and Swept-Back Wings. NACA RM No. L6L17, 1947.

TABLE I.– MODEL-SHAPE PARAMETERS

Configuration	Aspect ratio, A	Wing area (sq in.)	Maximum chord in stream direction (in.)	Thickness ratio, t/c
Triangular wing; $\epsilon = 26^\circ$	1.96	1.772	1.890	0.02
Triangular wing; $\epsilon = 45^\circ$	4.06	1.295	1.130	.03
Swept wing; $\Lambda = 36^\circ$	1.76	3.600	1.135	.11
Swept wing; $\Lambda = 45^\circ$	3.26	3.340	1.330	.09
Swept wing; $\Lambda = 63^\circ$	1.37	3.340	2.070	.06
Trapezoidal wing; $\theta = 40^\circ$	3.36	1.095	1.069	.06
Trapezoidal wing; $\theta = 30^\circ$	2.78	1.440	1.008	.09
Rectangular wing	1.74	1.972	1.069	.06
Rectangular wing	1.99	2.019	1.008	.09

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TABLE II.— TEST CONFIGURATIONS

[a, sting "a;" b, sting "b;" c, sting "c;" lw long windshield (only $\alpha \approx 45^\circ$); pc, evaluation of sting lifts by sting pressures]

Wing	Test configurations		
	M = 1.55	M = 1.90	M = 2.32
Triangular wing; $\epsilon = 26^\circ$	b, lw, pc 0° to 52°	b, c, lw 40° to 52°	a 0° to 50°
Triangular wing; $\epsilon = 45^\circ$	b, lw, pc 0° to 50°	------ ------	a 0° to 52°
36° sweptback wing	b 0° to 44°	b, c, lw 42° to 54°	------ ------
45° sweptback wing	b 0° to 45°	------ ------	a 0° to 50°
63° sweptback wing	b 0° to 41°	------ ------	a 0° to 52°
Trapezoidal wing; $\theta = 40^\circ$; tips beveled	b, lw, pc 0° to 50°	b, c, lw 42° to 54°	------ ------
Trapezoidal wing; $\theta = 40^\circ$; tips not beveled	b 0° to 10°	------ ------	------ ------
Trapezoidal wing $\theta = 30^\circ$; tips beveled	------ ------	b, c, lw 40° to 52°	------ ------
Trapezoidal wing $\theta = 30^\circ$; tips not beveled	------ ------	c 40° to 48°	a 0° to 52°
Rectangular wing; A = 1.74	b, lw, pc 0° to 50°	b, c, lw 42° to 54°	------ ------
Rectangular wing; A = 1.99	------ ------	------ ------	a 0° to 52°

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TABLE III.– MAXIMUM-LIFT-COEFFICIENT VALUES

Configuration	$C_{L_{max}}$		
	M = 1.55	M = 1.90	M = 2.32
Triangular wing; ϵ = 26	1.05	1.05	1.00
Triangular wing; ϵ = 45	1.10	-----	1.05
36° sweptback wing	1.10	1.00	-----
45° sweptback wing	1.10	-----	.95
63° sweptback wing	1.00	-----	.95
Trapezoidal wing; θ = 40°; tips beveled	1.15	1.10	-----
Trapezoidal wing; θ = 30°; tips not beveled	-----	1.05	1.00
Trapezoidal wing; θ = 30°; tips beveled	-----	1.05	-----
Rectangular wing; A = 1.74	1.15	1.05	-----
Rectangular wing; A = 1.99	-----	-----	1.00

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Figure 1.- General view of models tested.

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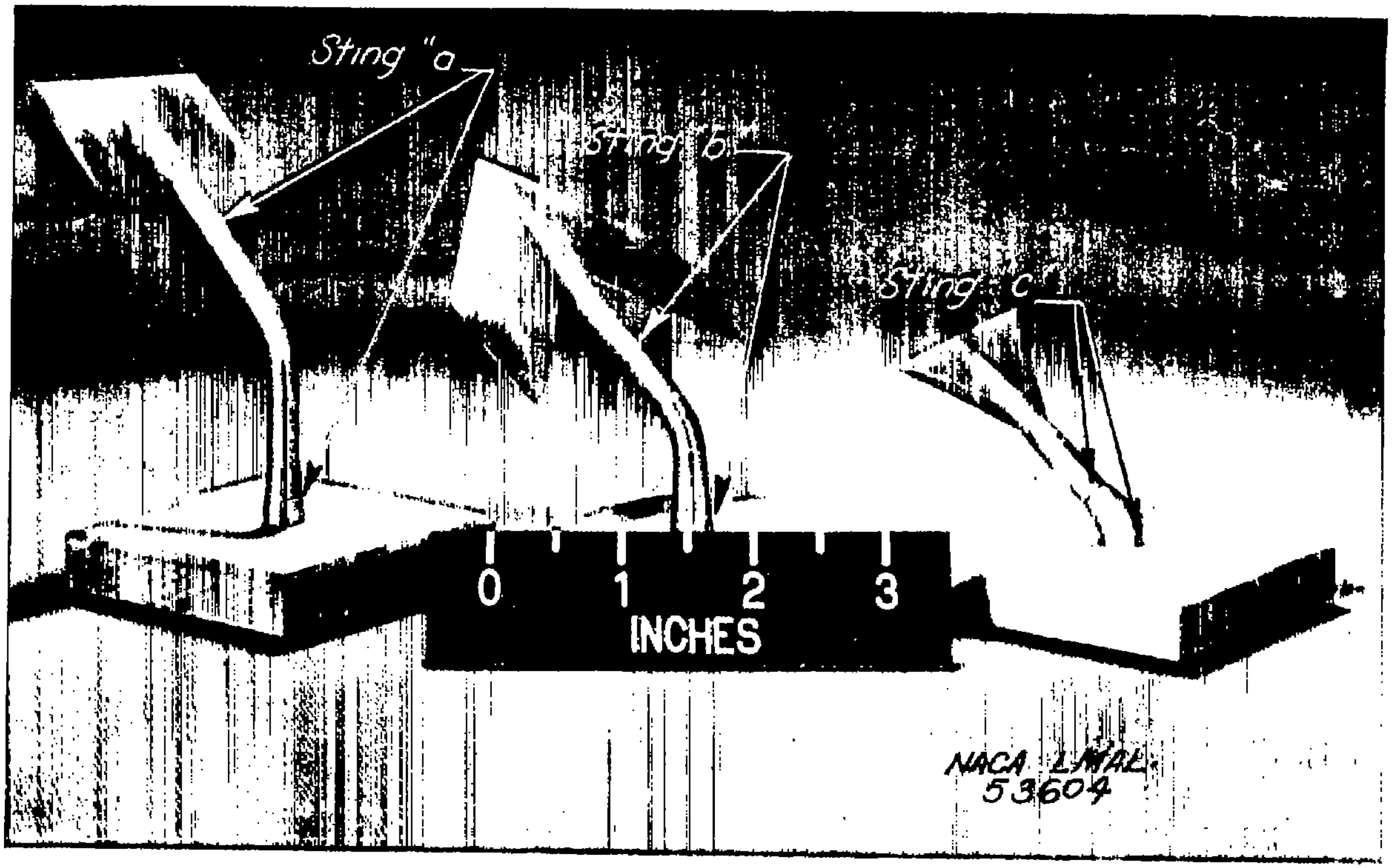

Figure 2.- Various stings used in tests. Stings bent 45°.

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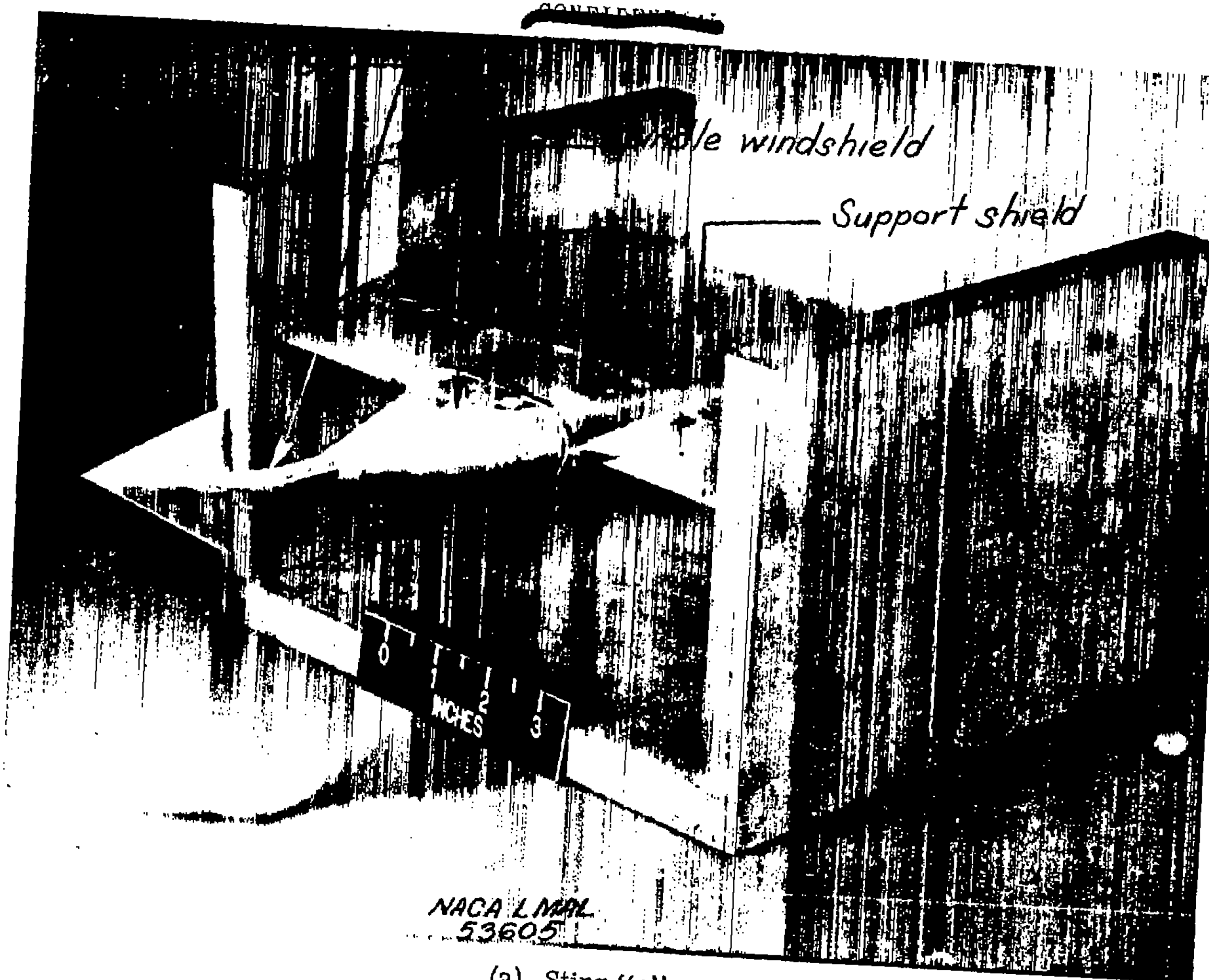

(a) Sting "c".

Figure 3.- Triangular wing mounted on various stings, showing support shield and spindle windshield used in the tunnel tests.

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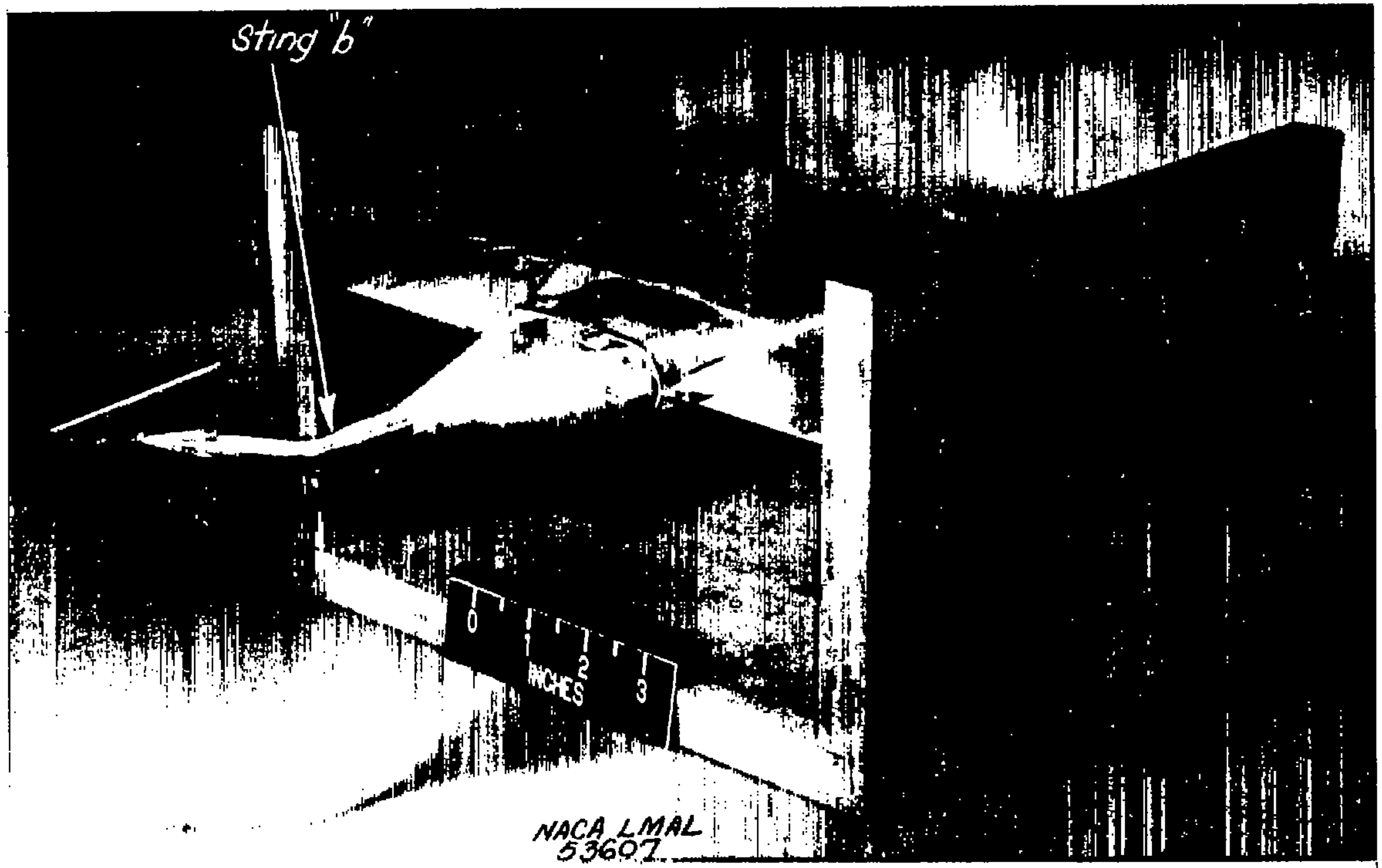

(b) Sting "b".

Figure 3.- Concluded.

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Figure 4.- Long windshield used to cover sting supports.

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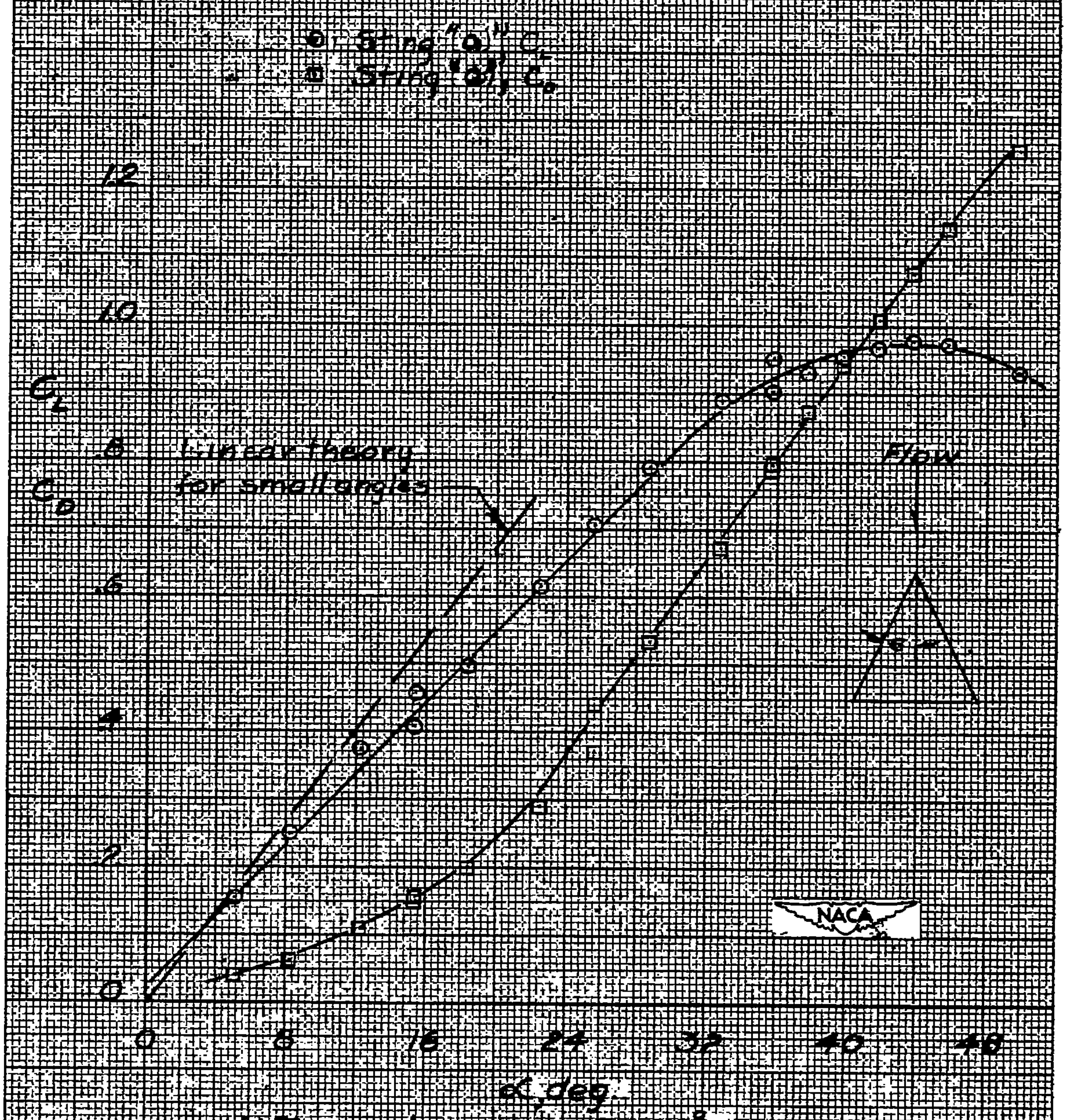

(a) Triangular wing; $\epsilon = 26°$.

Figure 5.- Variation of lift coefficient and drag coefficient with angle of attack. $M = 2.32$.

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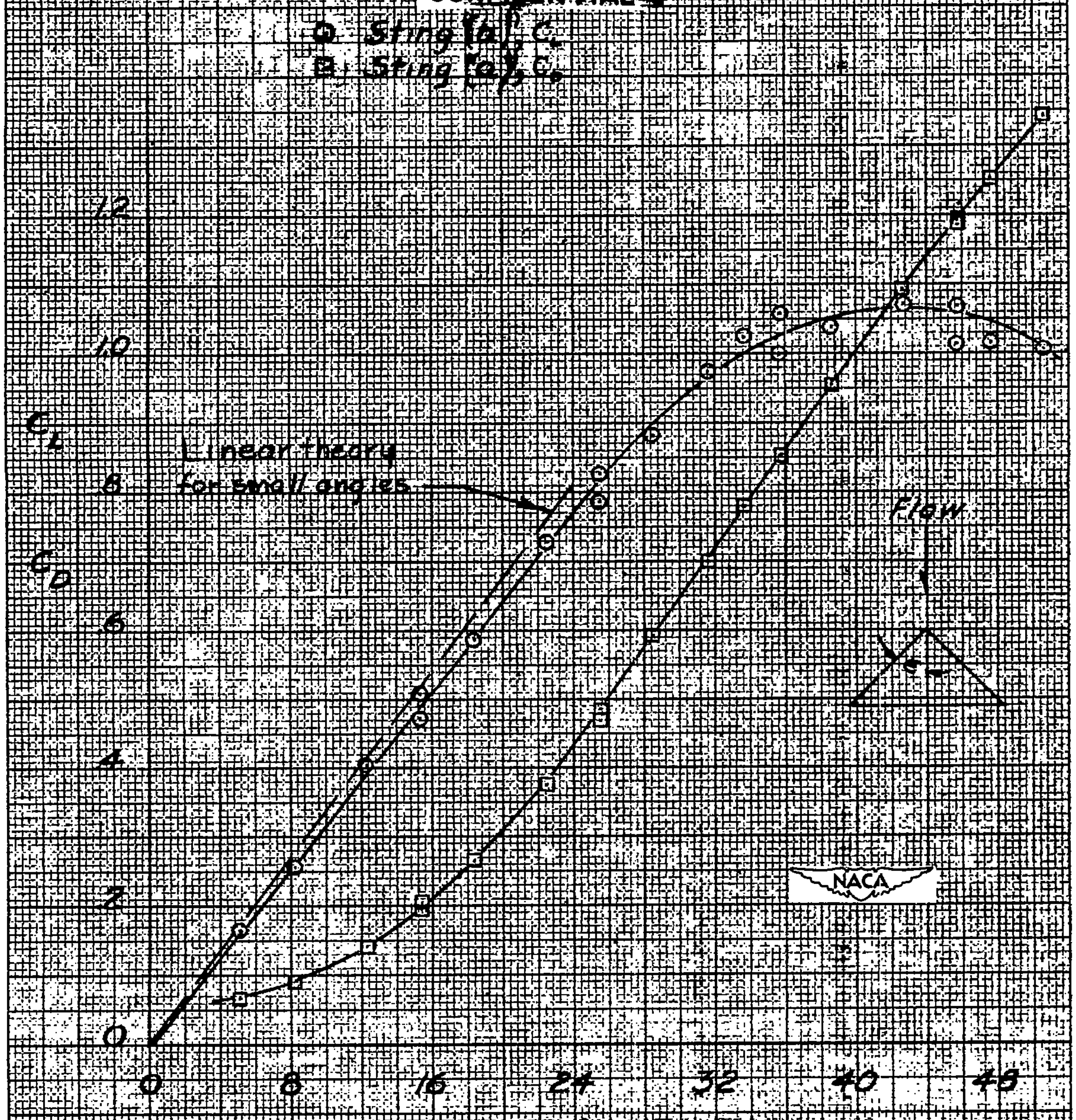

(b) Triangular wing; ε = 45°.

Figure 5.- Continued.

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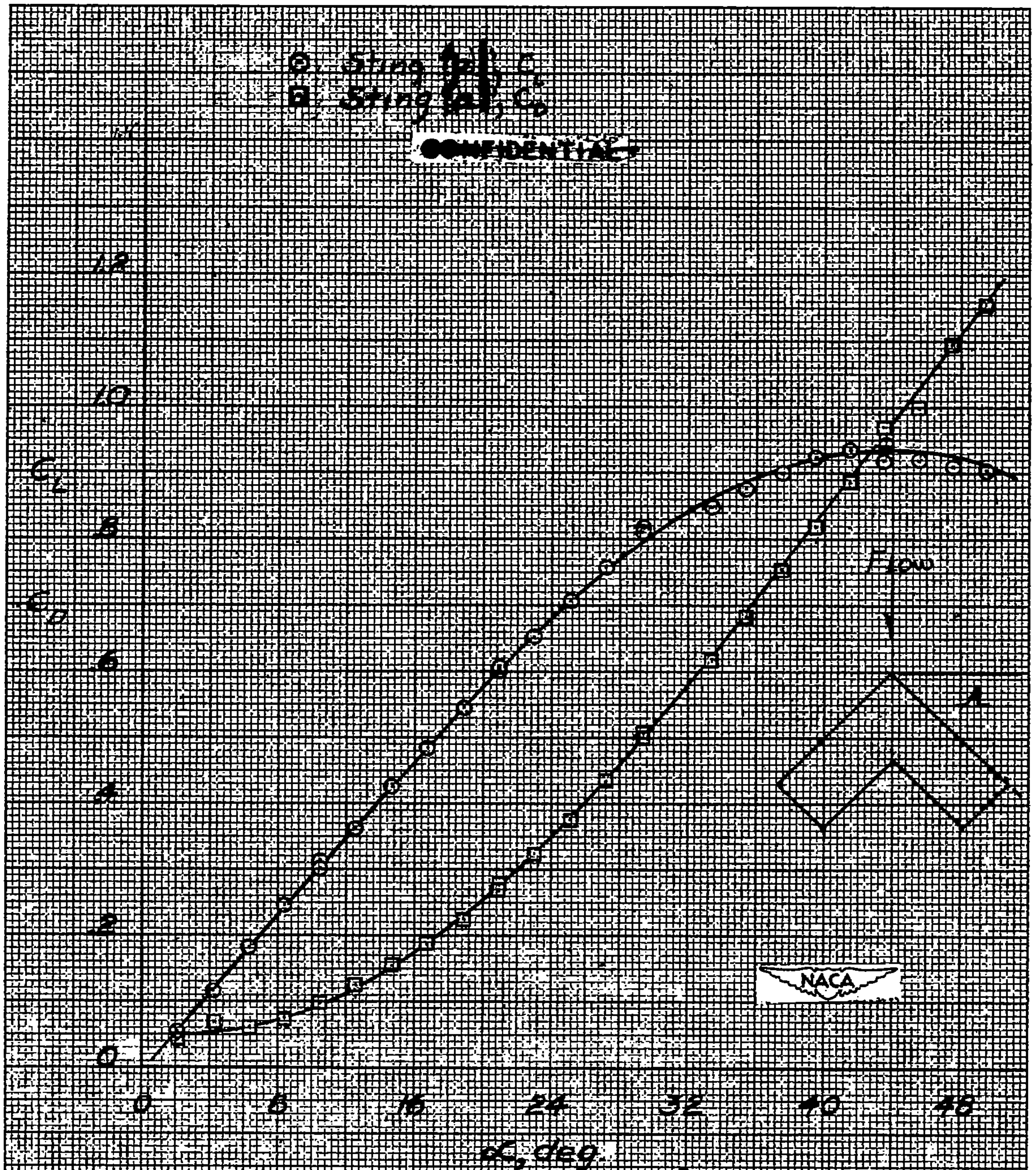

(c) Swept wing; Λ = 45°.

Figure 5.- Continued.

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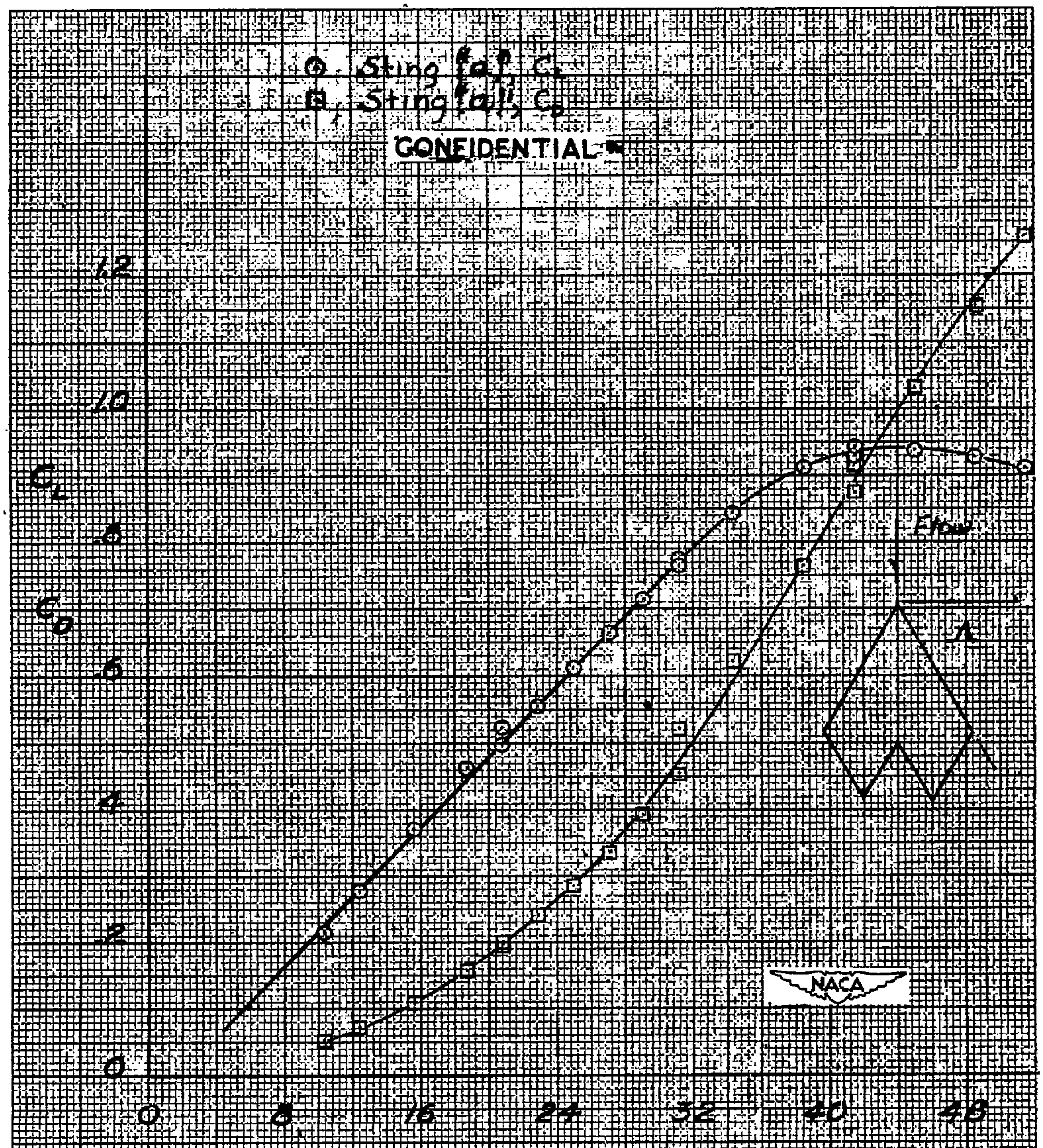

(a) Swept wing; Λ = 63°.

Figure 5. – Continued.

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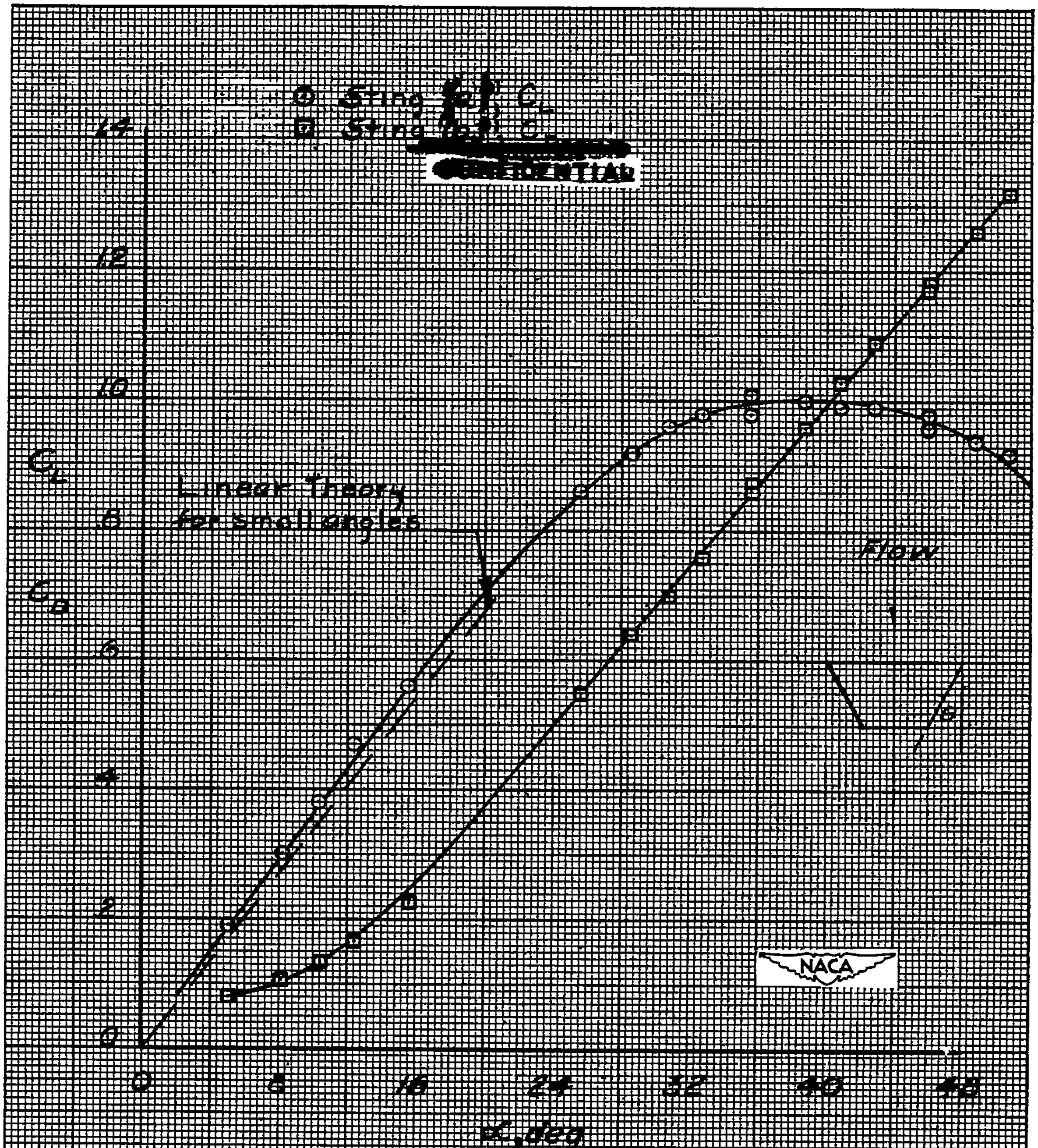

(e) Trapezoidal wing, $\theta = 30°$; tips not beveled.

Figure 5.- Continued.

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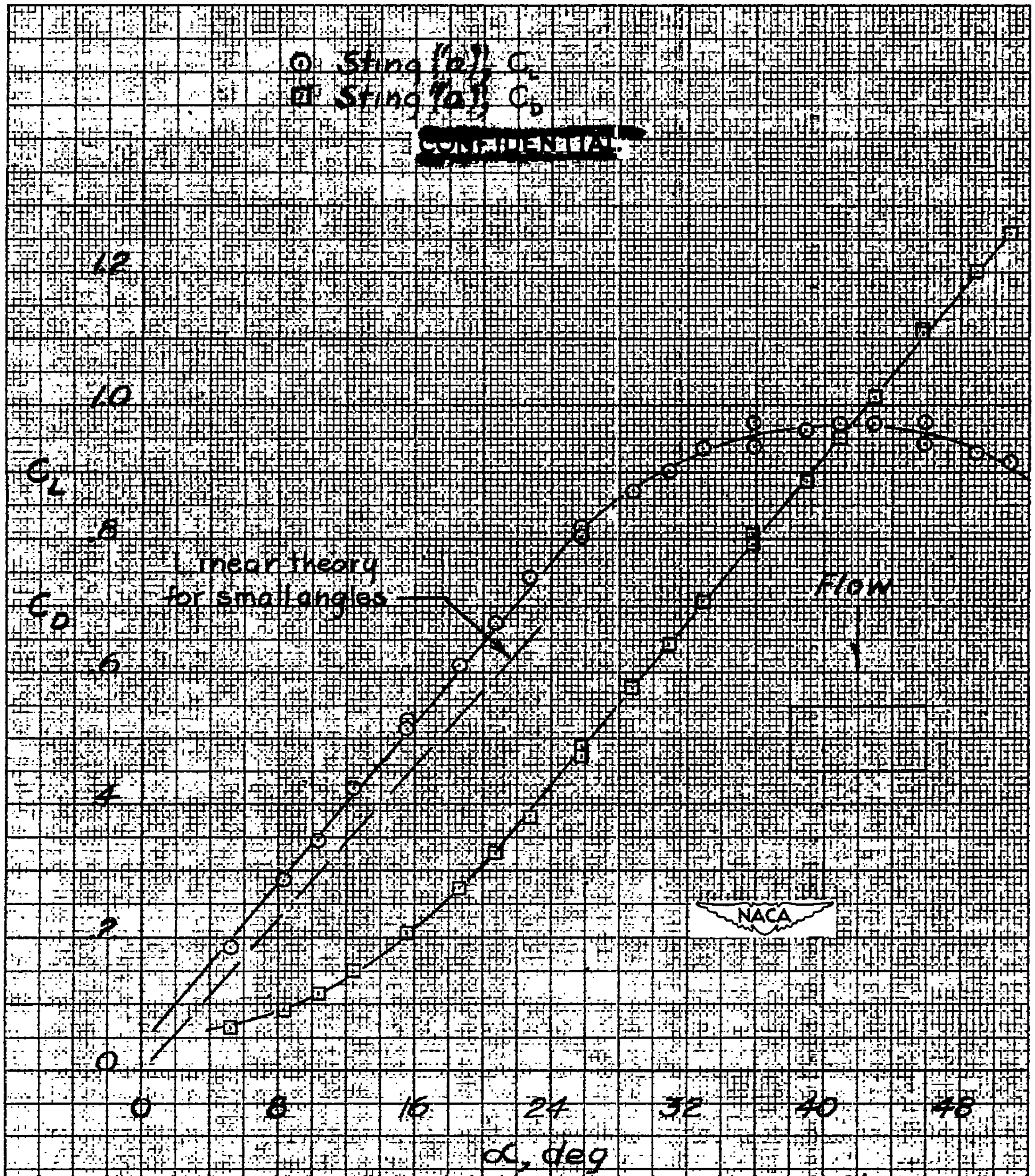

(f) Rectangular wing; A = 1.99; $\frac{t}{c}$ = 0.09.

Figure 5 .- Concluded.

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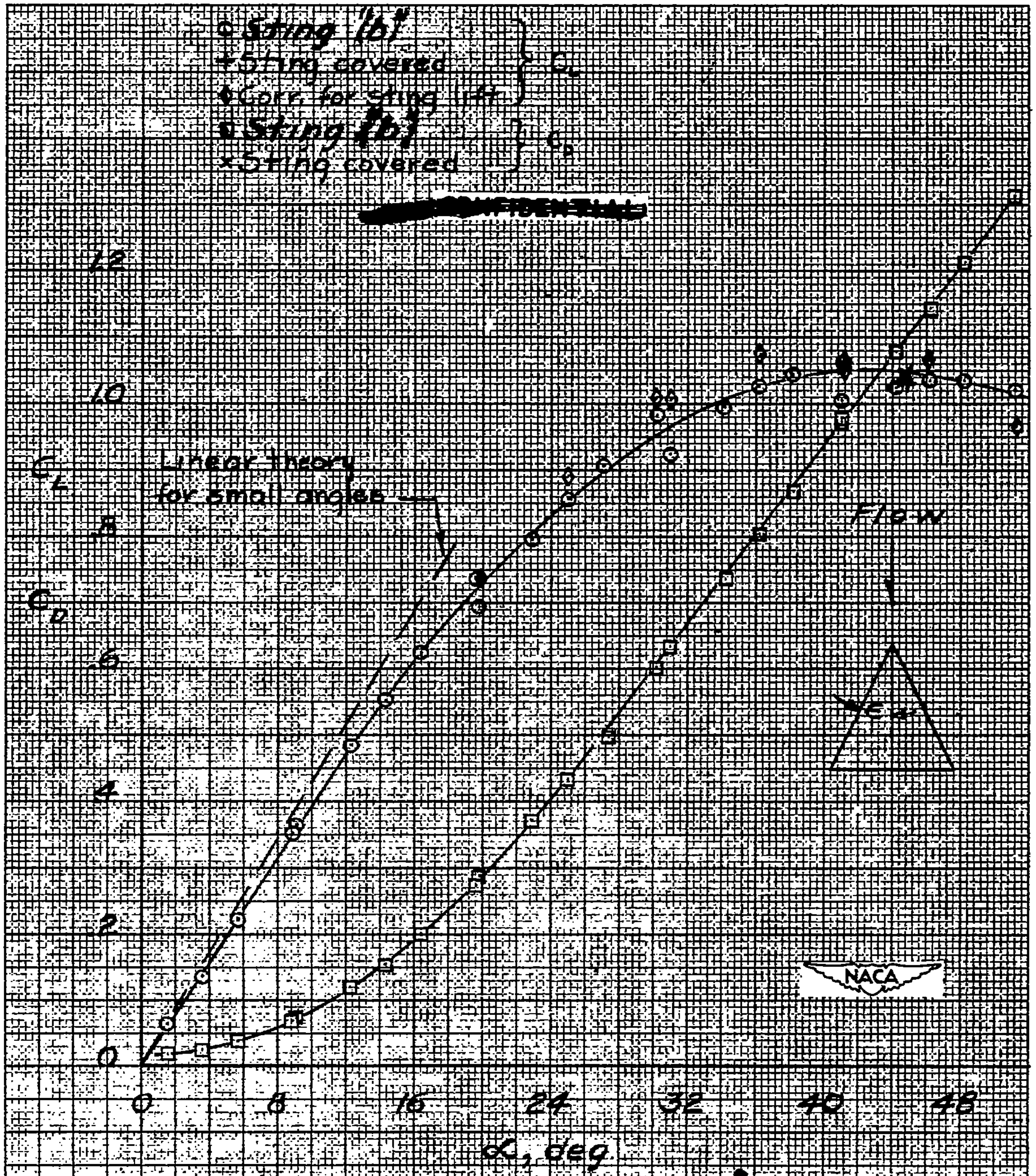

(a) Triangular wing; ε = 26°.

Figure 6. - Variation of lift coefficient and drag coef[redacted] with angle of attack, M = 1.55.

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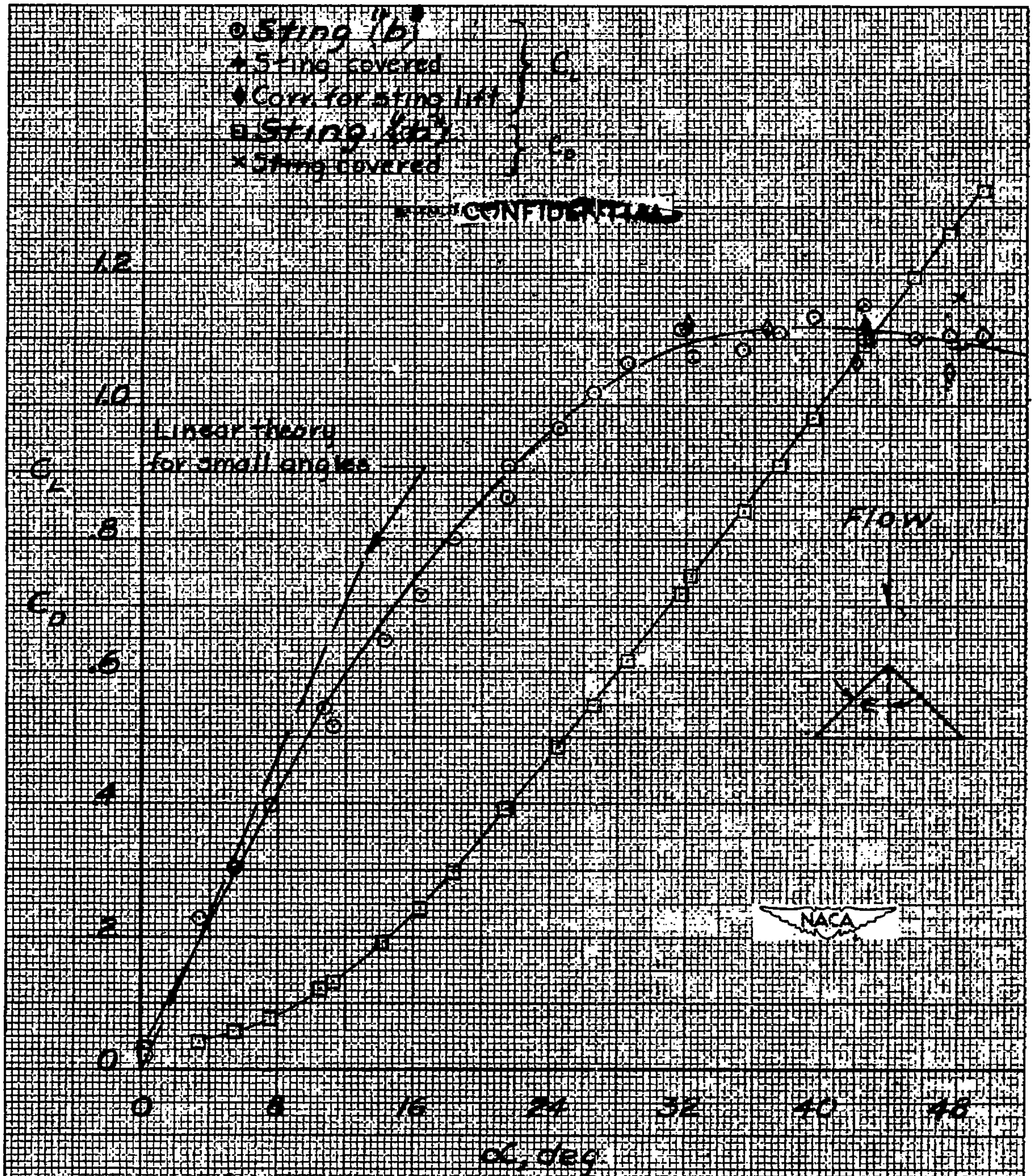

(a) Triangular wing; ε = 45°.

Figure 6. - Continued.

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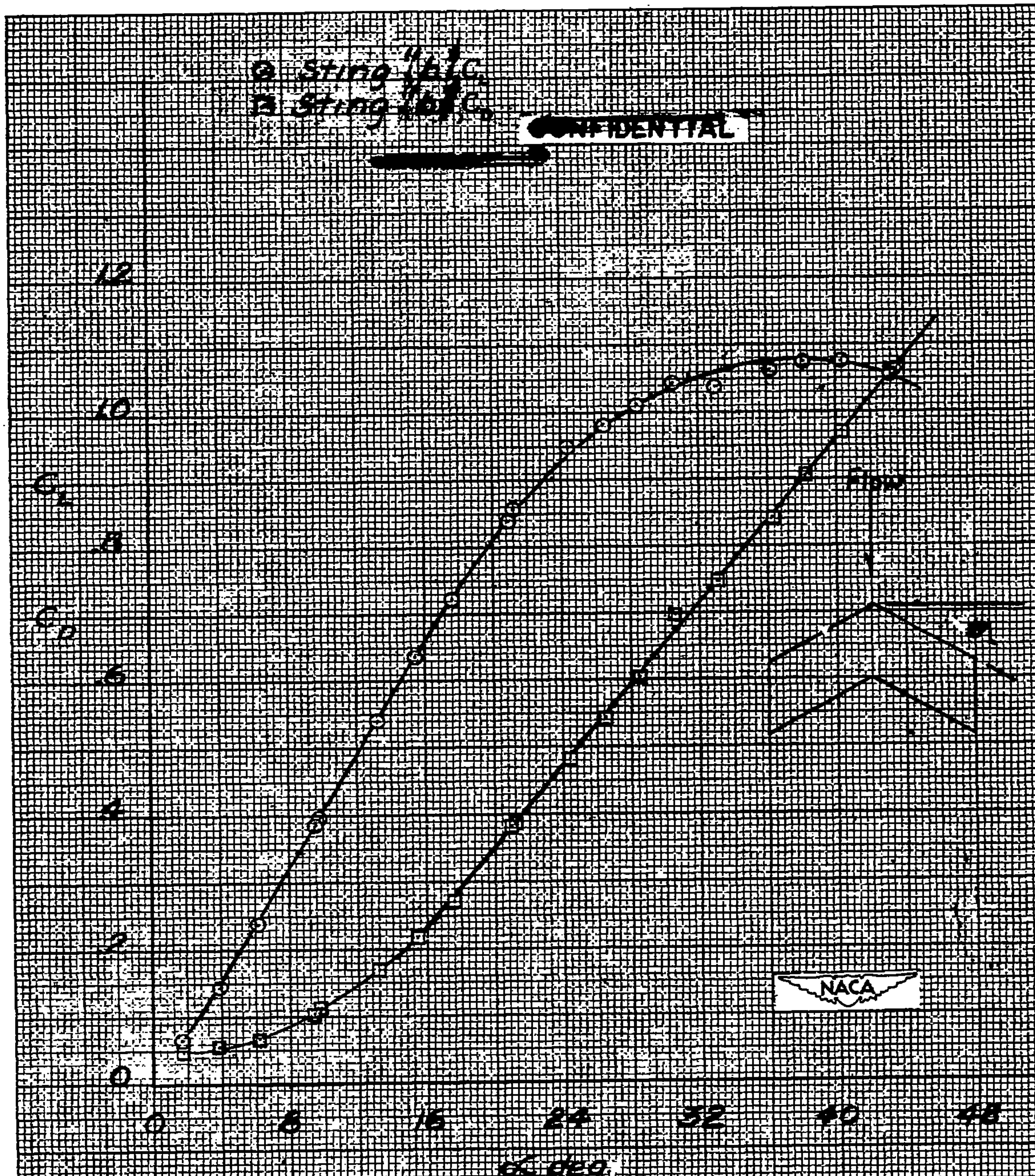

(c) Swept wing; Λ = 36°.

Figure 6. - Continued.

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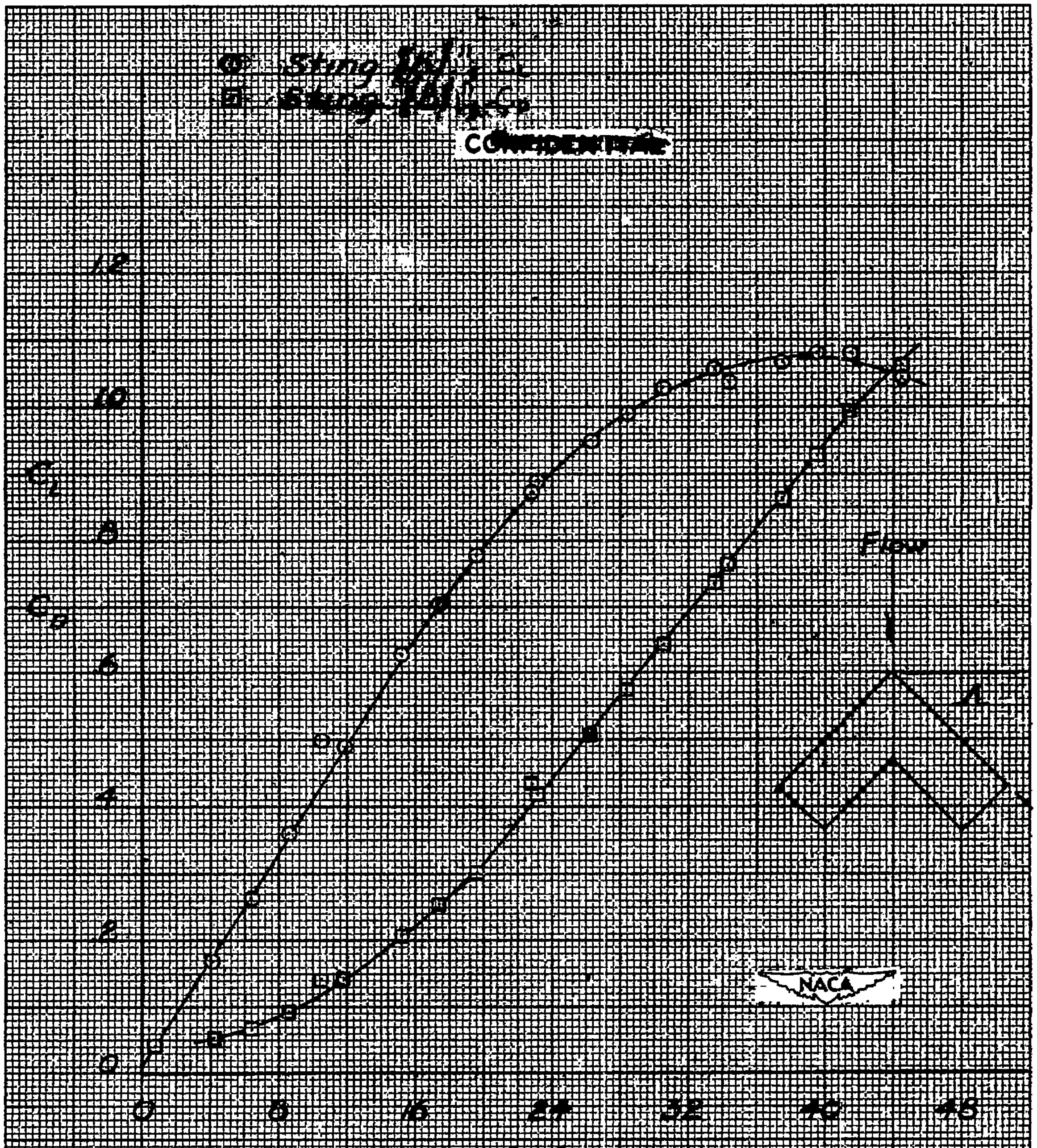

(d) Swept wing; Λ = 45°.

Figure 6.- Continued.

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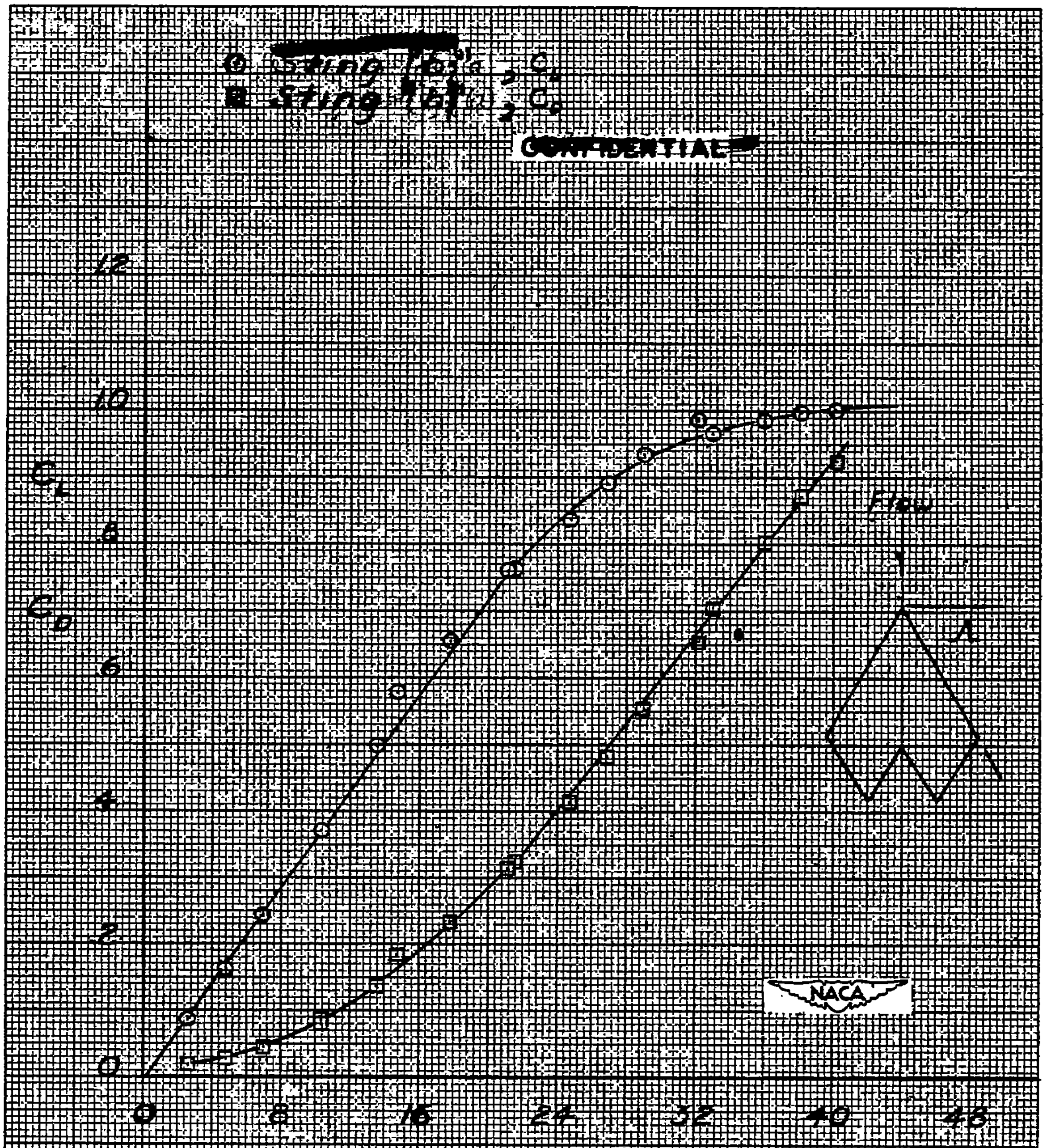

(e) Swept wing; Λ = 63°.
Figure 6 .- Continued.

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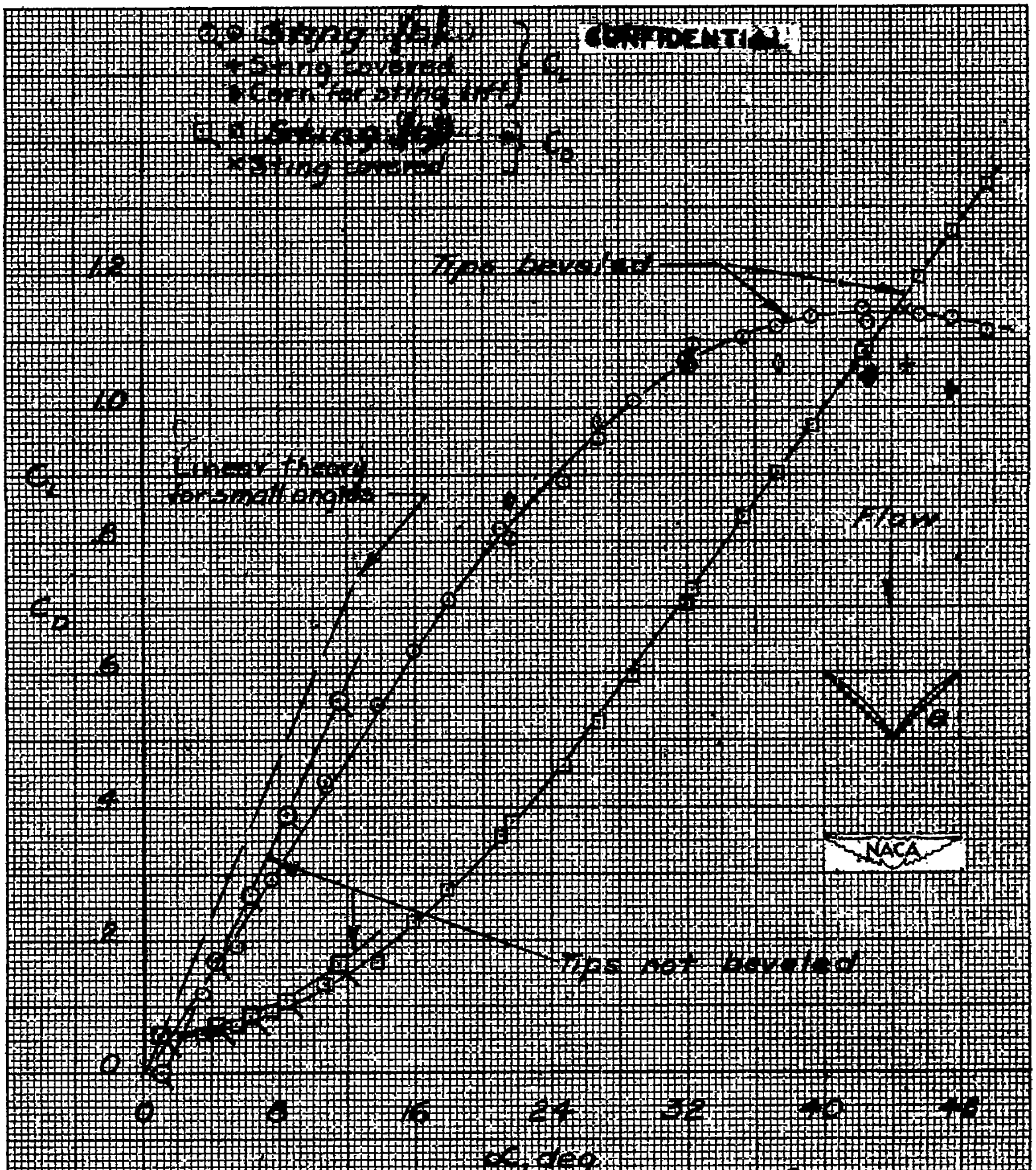

(f) Trapezoidal wing; $\Theta = 40^{\circ}$

Figure 6. - Continued.

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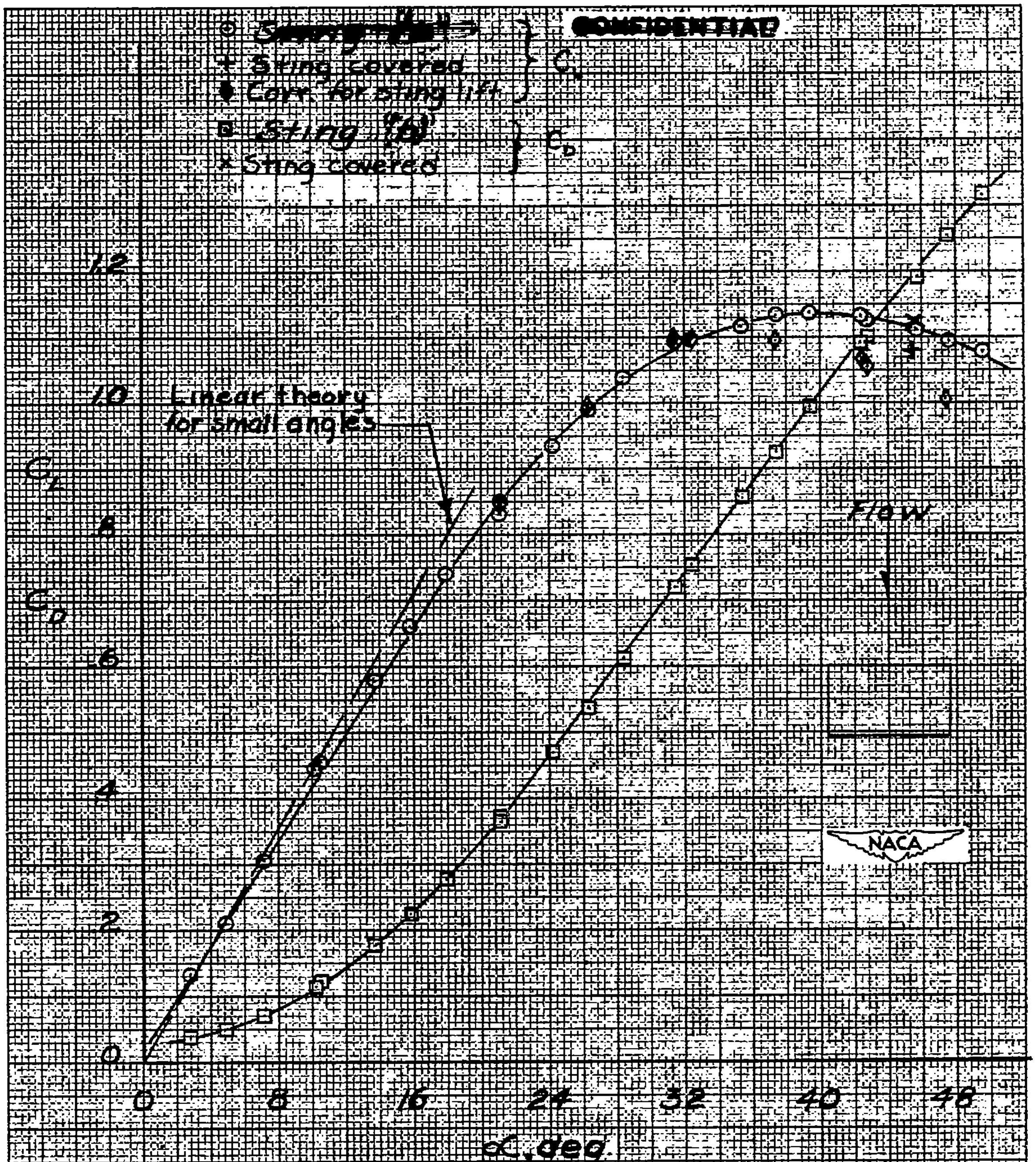

(g) Rectangular wing; $A = 1.74$, $\frac{t}{c} = 0.06$.

Figure 6. - Concluded.

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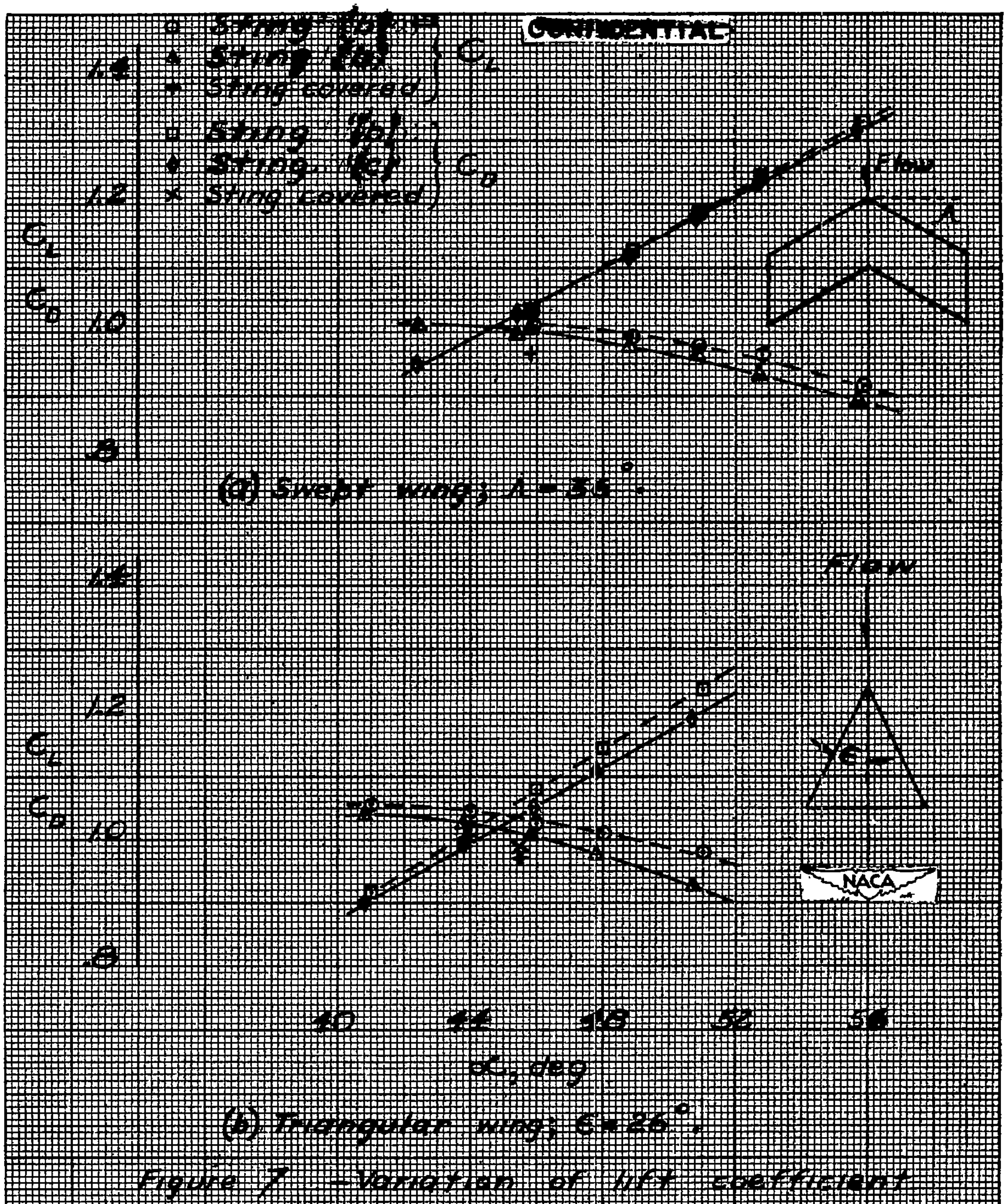
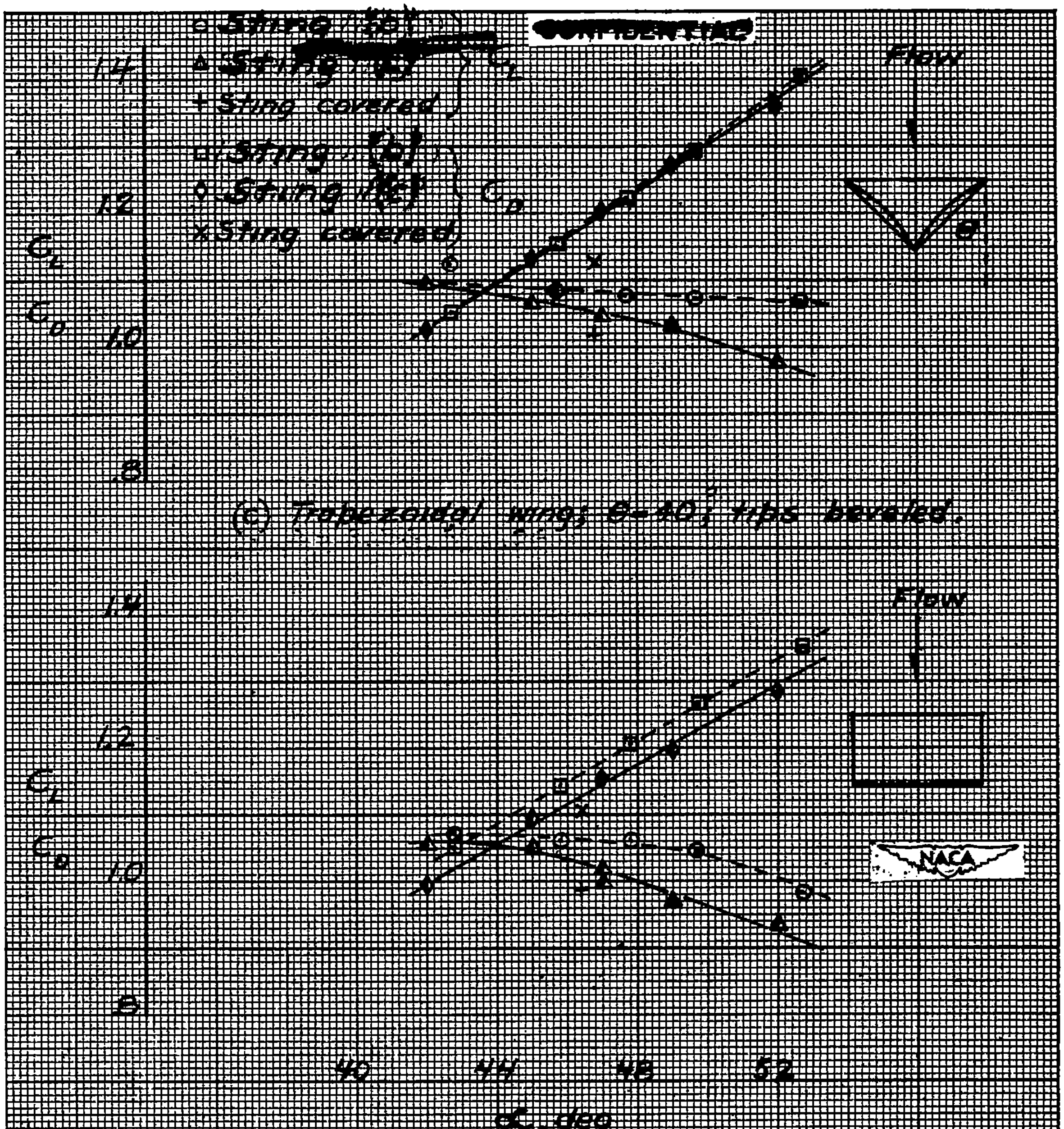


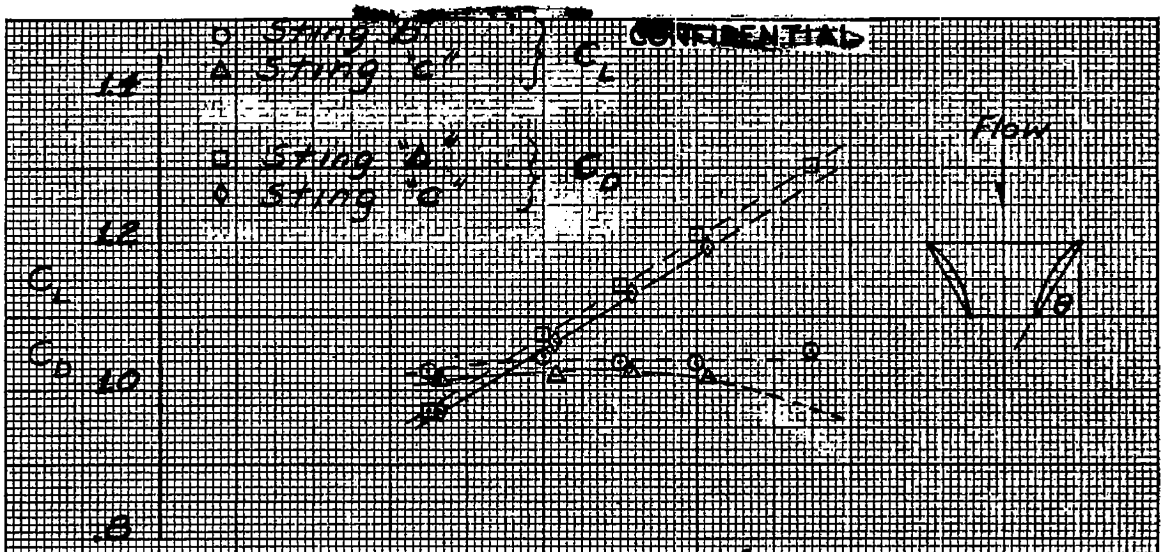
Figure 7.- Variation of lift coefficient and drag coefficient with angle of attack, M=1.90.



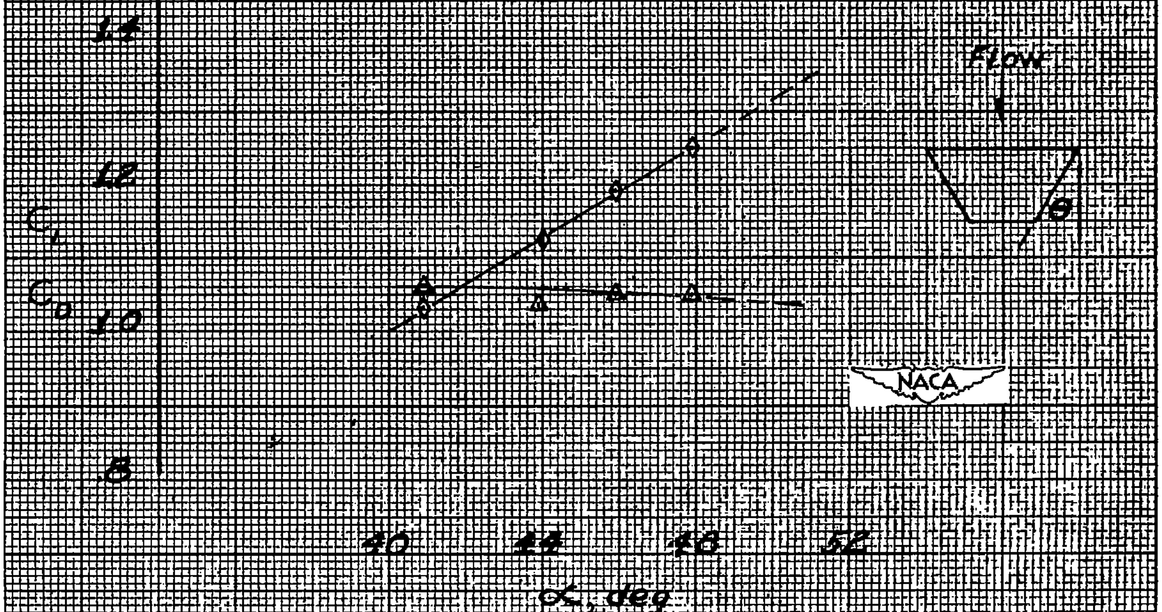
(c) Trapezoidal wing; θ=40°; tips beveled.

(d) Rectangular wing; A=1.74; $\frac{t}{c}$=.06.

Figure 7.- Continued.



(e) Trapezoidal wing; θ = 30°; tips beveled.

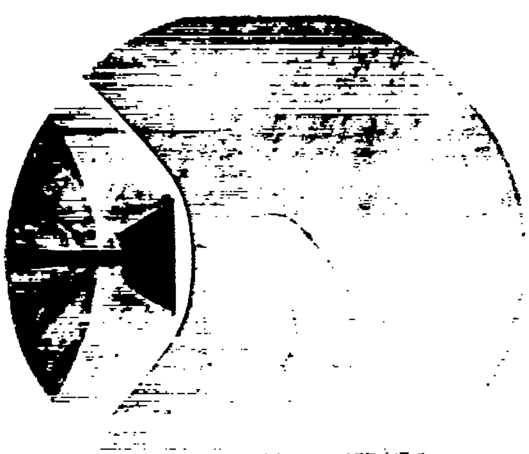


(f) Trapezoidal wing; θ = 30°; tips not beveled.

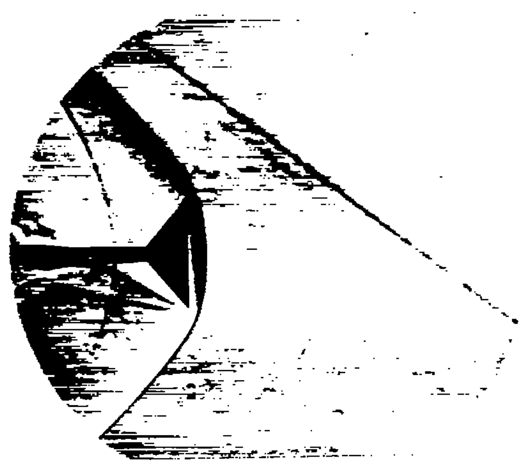
Figure 7.- Concluded.

Vertical knife edge

Horizontal knife edge



Vertical knife edge



Horizontal knife edge

(a) Trapezoidal wing; $\Theta = 40^{\circ}$; tips beveled.

Figure 8.- Schlieren photographs of wings operating at maximum lift. M = 1.55.

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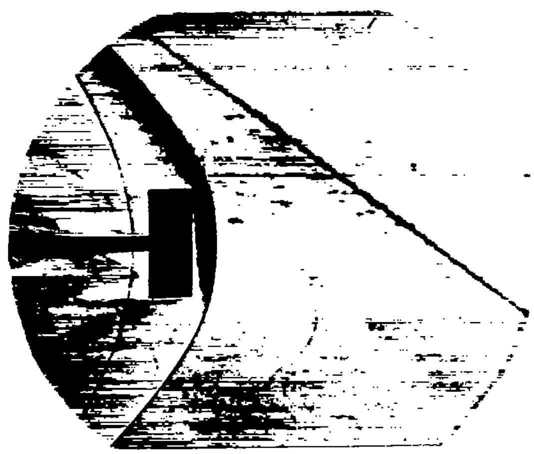
Vertical knife edge

Horizontal knife edge

Vertical knife edge



Horizontal knife edge

(b) Rectangular wing; $A = 1.74$; $\frac{t}{c} = 0.06$.

Figure 8.- Concluded.

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